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AN ANALYSIS OF SOME FREE-AIR OBSERVATIONS IN THEIR RELATION TO PRECIPITATION

By V. E. JAKL

In a previous paper by the writer [1] a few diurnal series of free-air observations were reproduced graphically to illustrate the time-altitude changes in temperature accompanying pronounced changes in temperature at the surface. Since then many more series of observations by means of kites have become available, and an examination of these has been made with a view to selecting such as would be appropriate to the study of changes in free-air conditions leading up to rain or snow. The criterion for deciding which series would be suitable for reproduction was simply that the observations should extend to about 3,000 meters or more in altitude, and that they should be immediately or very soon followed by precipitation.

The purpose of this study was to correlate the sequence of temperature changes—and incidentally, of course, changes in other recorded elements—with the formation of precipitation. It has been thought helpful in interpreting the graphs to consider them separately by types, according to the direction of the surface wind prior to and during the occurrence of precipitation, and the position of the precipitation area with respect to the surrounding pressure distribution. Briefly, the types in this respect are those given in a preliminary paper on this subject by the writer,[2] and are as follows: (1) With easterly and northeasterly surface winds—therefore in the northern portion of a LOW area, or to the north of the nearest low pressure center; (2) with northwesterly surface winds, or in the rear of LOWS or front of HIGHS; (3) in the region of wind shift lines—ordinarily the south portion of LOWS; (4) with general southerly winds, or the southeast and east portions of a LOW.

Observations suitable for this study comprise only a small portion of all the observations made, the reasons being as follows: Kite flights are seldom deliberately made during the prevalence of rain or even when rain is imminent, and never when thunderstorms threaten, owing to the danger of destruction of kites and instrument in the former case, and additional danger of injury to personnel in the latter. During snowstorms there is ordinarily no danger of accident or injury, but as a rule observers prefer to complete their flights before the beginning of snow, or, when snow is falling, to delay starting the flight until after the snow has ended, owing to the fact that higher flights are possible in fair weather.

Records suitable for this study are therefore largely the fortunate outcome of series of flights terminated by precipitation, or in some cases, of series of flights in which the final flight was actually overtaken by storm. Notwithstanding these difficulties, the accumulation of records during the past few years offers the choice of quite a number of instructive series of free-air observations related to the occurrence of precipitation.

Some explanation is also appropriate here as to the meaning of "diurnal series." Apart from the ordinary routine at kite stations of making a single flight each day to as high an altitude as possible, the program of work includes the making of a series of observations at occasional intervals during the year when weather and wind permit. These observations consist of a succession of kite flights, one immediately following another, until about eight flights or so are made covering a period usually extending from the morning of one day to the afternoon of the next. Sometimes these attempted series are terminated after only a few flights have been obtained, on account of threatening weather or diminishing wind.

Limitations of space restrict the reproduction of the available series to a few well-developed specimens representing each of the so-called types of precipitation. This rather arbitrary division does not pretend to cover all possible types of precipitation occurring in the United States. This paper, moreover, necessarily deals only with the middle sections of the country, particularly the central portion, where, of all sections having primary aerological stations, free-air work has been carried on longest and most intensively. Furthermore, the discussion does not pretend to be a rigid analysis of the free-air processes attending precipitation. It is a presentation of some of these series of observations in "picturized" form, accompanied by such interpretation of them as the writer has felt competent to make.

No attempt has been made to interpolate the temperatures at the various altitudes with a view to making the altitude curves represent synchronous temperatures from the surface to the highest observation. In other words, the temperatures have been plotted at their respective altitudes without regard to time.

It had been hoped that charts of sea-level pressure would be available to accompany all these graphs, thereby helping to visualize the conditions they are intended to portray. It was found, however, that in only a few instances have the times of regular observation, on which the weather maps are based, coincided, even roughly, with the times of free-air observation and precipitation. Where these requirements of approximate simultaneity have been met, charts have been reproduced in connection with the graphs to which they refer; in the other cases it is thought that to reproduce them would serve no useful purpose. In this connection it may be pointed out that charts appropriate to Figure 4 are given in considerable detail in an article relating to the same storm that appeared in an earlier number of the REVIEW, reference to which is made in the text pertaining to that graph.

Comparison of free-air observations from stations 100 to 200 miles apart would be very interesting were such available. The distance between stations is, however,

[1] Jakl, V. E., Some Observations on Temperatures and Winds at Moderate Elevations above the Ground. MO. WEATHER REV., June, 1919, 47: 367-373.
[2] Jakl, V. E., A Preliminary Study of Precipitation in Relation to Winds and Temperature. MO. WEATHER REV., January, 1924, 52: 18-22.

never less than 300 miles. Hence no useful comparisons can be made between those few observations which weather conditions at two or more stations permitted to be made simultaneously. The different graphs wil be considered in groups in the numerical order of the types into which they fall.

(1) The series of January 27–28, 1916, the graph for which is shown in Figure 1, is cited to show an apparent

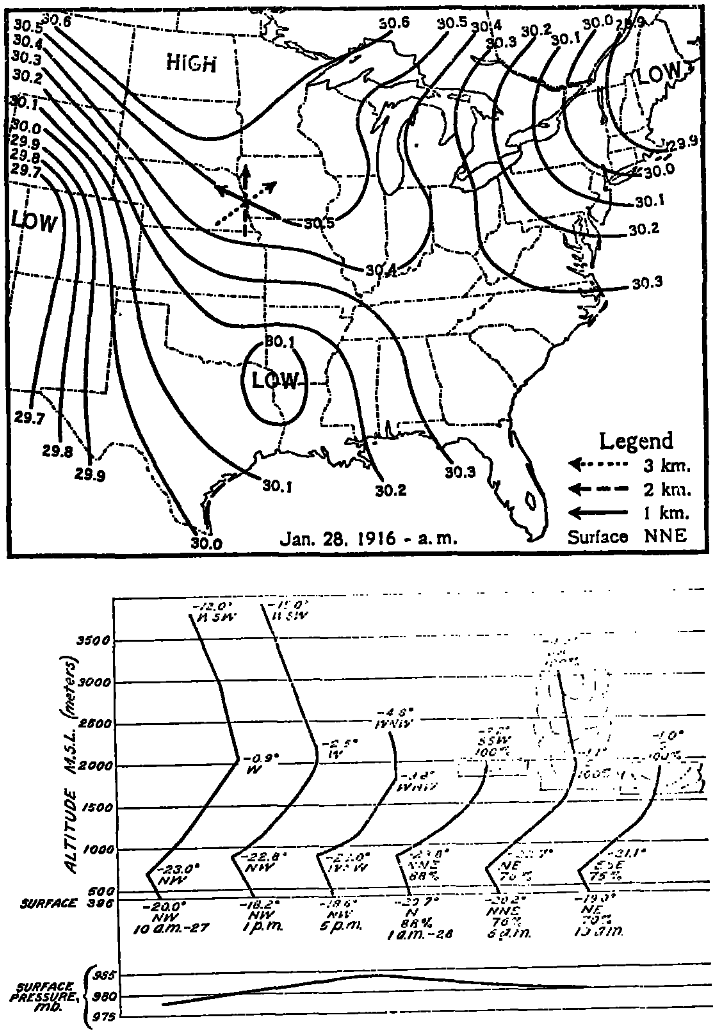

FIG. 1.—Sequence of free-air conditions at Drexel, January 27–28, 1916. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation. Upper figure shows sea-level pressure at 7 a. m., ninetieth meridian time, January 28, and free-air winds over Drexel at approximately corresponding time

exception to the general rule that inversions are associated with drier air than that immediately below. Owing to the low temperatures that prevailed at the surface, the determinations of surface humidity from whirling psychrometer observations, which usually form the reference basis for reading free-air humidities recorded aloft, are not in this case reliable. Therefore humidities have not been entered on the graph except in the later flights of the series, where exposure of the kite instrument to dense clouds gave a saturation record as a reliable base of reference.

Considered in connection with the pressure distribution, which showed higher pressure north of Drexel, this series of observations apparently represents an ideal case of "warm-front" precipitation. However, in this case clouds were observed principally in that portion of the air column extending from the inversion level upwards throughout which a lapse rate somewhat less than the moist adiabatic for the existing temperature prevailed. No important change in temperature is shown in the vertical column from the morning of the 27th to the morning of the 28th, but it is apparent from the graph that clouds and precipitation formed soon after the wind in the upper levels changed to southerly. If, from the facts presented, one is disinclined to attribute the snowfall to a "warm-front" process, an alternative explanation is possible by supposing that the lapse rate above the inverson eventually became sufficient to cause vertical convection. This supposition is given credence by the fact that the snowfall was light until after the last flight, the snow having begun at 1.30 a. m. and ended about midnight on the 28th. Since the surface wind remained northeast and the pressure fell to about 6 a. m. of the

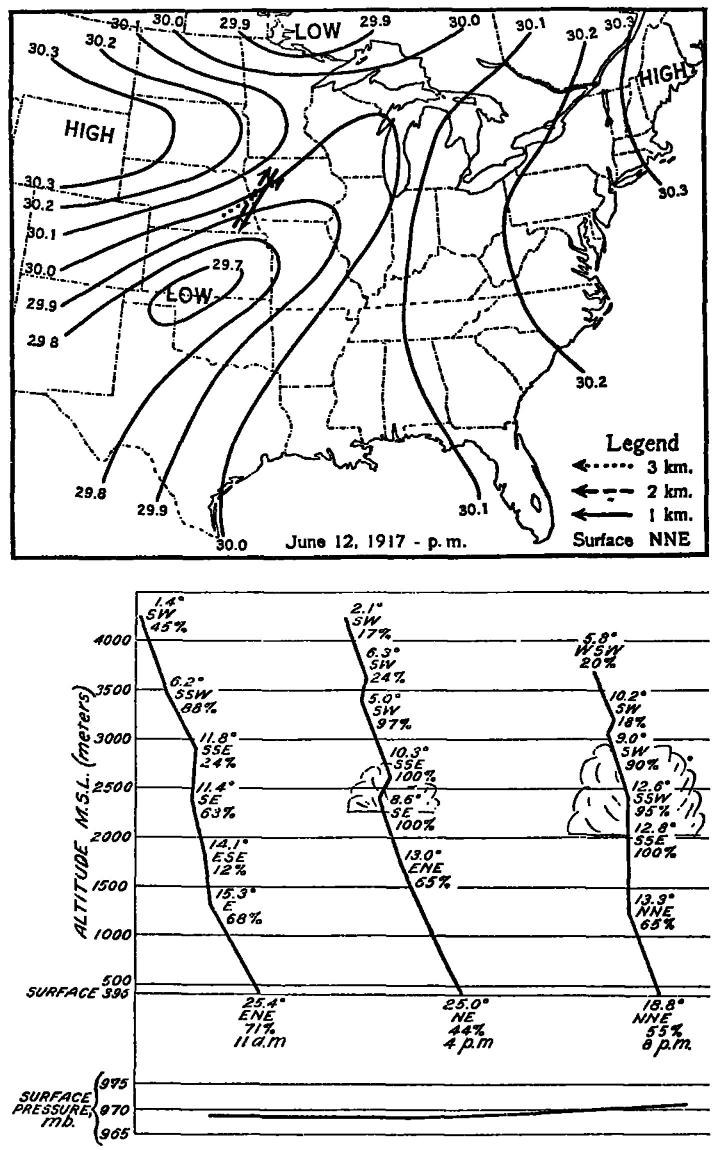

FIG. 2.—Sequence of free-air conditions at Drexel, June 12, 1917. Upper figure shows sea-level pressure at 7 p. m., ninetieth meridian time, June 12, and free-air winds over Drexel at approximately corresponding time

29th, it is apparent that the wind turned clockwise with altitude during the time that the snow fell.

Figure 2 is a graph of the series of three flights of June 12, 1917, showing free-air conditions up to about three hours before precipitation began. The wind veered with altitude from northeasterly on the ground to southwesterly aloft, but owing to lack of pressure fall and necessary convergence or other cause to impel ascent of air, precipitation did not occur until the pressure rose. The rise in pressure, occurring after the last flight of the series, was evidently accompanied by a change from clockwise to counterclockwise turning of the wind with altitude, resulting in an underrunning effect on the southerly winds aloft by the cold northerly winds near the ground. Evidence of the impending change to counterclockwise is shown on the graph by the abrupt change with altitude from north-northeast to south-southwest above 1,250 meters in the last flight; also by rising pressure and the fact that the surface wind changed from northeast to northwest soon after precipitation began.

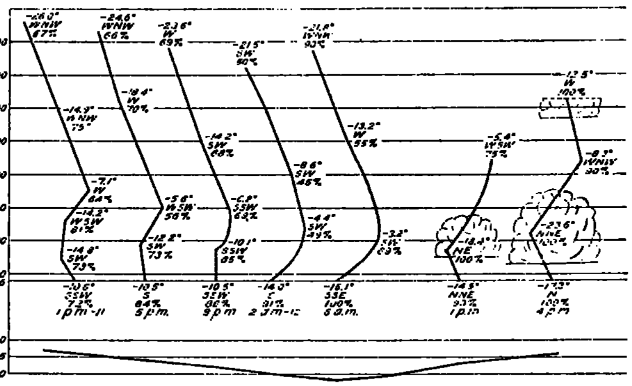

FIG. 3.—Sequence of free-air conditions at Drexel, December 11–12, 1917. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation

A statistical study of changes in direction with altitude for the United States by C. LeRoy Meisinger,[3] shows that in passing from the front to the rear of a LOW through the northern quadrants, the change from clockwise to counterclockwise turning with altitude is found on the average in that portion of the LOW where the surface winds are northeast. Precipitation in this north portion of LOWS therefore occurs with both kinds of turning, and often with both kinds in the same storm, in the latter case veering with altitude being followed by backing with altitude. On June 12, 1917, precipitation did not begin at Drexel until the change to counterclockwise turning with altitude took place. It will be noted that there was a rapid rise in altitude of the inversion that first became evident as a slight interruption of the lapse rate at about 1,500 meters. Kites do not show fine distinctions in wind directions, but the observed change in direction from beginning to end of the series was sufficiently large to be accepted as authentic. Increasing humidity and cloudiness, having as an upper limit the surface of temperature discontinuity, resulted as the winds aloft veered from easterly to more southerly and southwesterly, and temperature became higher at progressively higher altitudes. While the record of humidity in portions of the clouded area in the third flight was actually slightly less than at corresponding levels in the second flight, this was apparently due to the clouds being somewhat broken at the time they were penetrated by the kite. It will be noted that in the clouded area below the inversion a decrease in the lapse rate resulted as the inversion rose and the temperature fell in the northeasterly winds below. This appears to be a further reason why no precipitation occurred until pressure rose attended by underrunning northeasterly to northwesterly winds.

The series of December 11–12, 1917 (fig. 3) shows the conditions attending a very light snowfall when wind near the ground changed from southerly to north and northeasterly. The cold northeasterly winds from the body of the HIGH to the northwest simply displaced the southerly winds at the lower levels, while the upper winds remained about west. Such light precipitation as occurred was apparently due to the stratus cloud forming at the top of the northeast wind as a result of turbulence and mixture with the previously warmer air of south component. This vertical structure of the air is typical of free-air conditions attending the approach of cold waves.[4]

The series of February 11–12, 1919 (fig. 4), is another illustration of the conditions preceding precipitation occurring with northeast surface wind and southerly wind aloft. The surface wind became northeast when precipitation began three hours after the end of the last flight, and remained northeast throughout the 13 hours during which precipitation occurred with falling pressure. It will be noted that a marked inversion began in the lower levels as soon as the winds changed to a general southeasterly direction from the previous southwesterly direction soon after 1 a. m. This inversion was due to slowly rising temperature above and rapidly falling temperature below. The last altitude graph shows a fall in temperature at about 1,200 meters with an inversion immediately above, but no discontinuity in wind direction, indicating that the southeast wind below the inversion, with its attendant cloudiness, had a different source from the southeast wind at and above the inversion. The falling temperature evidently had its origin east or northeast of Drexel, while the rising temperature and low humidity at and above the inversion at 1,600 meters can be attributed to continued inflow from regions far to the south or southwest. Subsequent

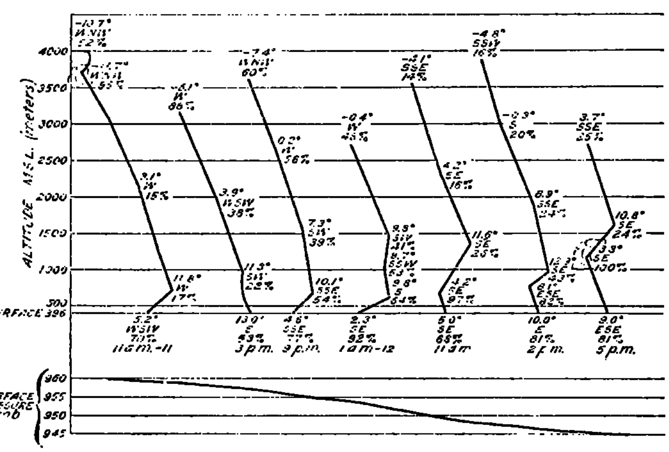

FIG. 4.—Sequence of free-air conditions at Drexel, February 11–12, 1919

observations are confined to the surface and show that the wind backed to northeast and temperature and pressure fell.

An analysis of this LOW, which caused widespread precipitation, was made by the late Dr. C. LeRoy Meisinger (The Great Cyclone of Mid-February, 1919, Mo. WEATHER REV., October, 1920, 48: 582–586), his explanation of the cause of the attendant precipitation being based on his acceptance of the "warm and cold front" theory. In view of the fact that most of the precipitation at Drexel in this storm occurred with a northeast surface wind and falling pressure, this explana-

[3] Meisinger, C. LeRoy, The Preparation and Significance of Free-Air Pressure Maps for the Central and Eastern United States, MO. WEATHER REV. SUPPLEMENT NO. 21.

[4] MO. WEATHER REV., June, 1919, 47: 367–373.

tion appears plausible. However, as in the case of January 27–28, 1916 (fig. 1), an additional explanation appears justified to the effect that precipitation was caused by a moist adiabatic gradient resulting in the upper levels where southerly winds prevailed, surmounted by cold southwest winds at still higher levels. It should be noted in this connection that precipitation began first on the eastern and southeastern sides of the LOW, where no "steering line" was apparent, and gradually developed successively over the northern and western portions of the LOW.

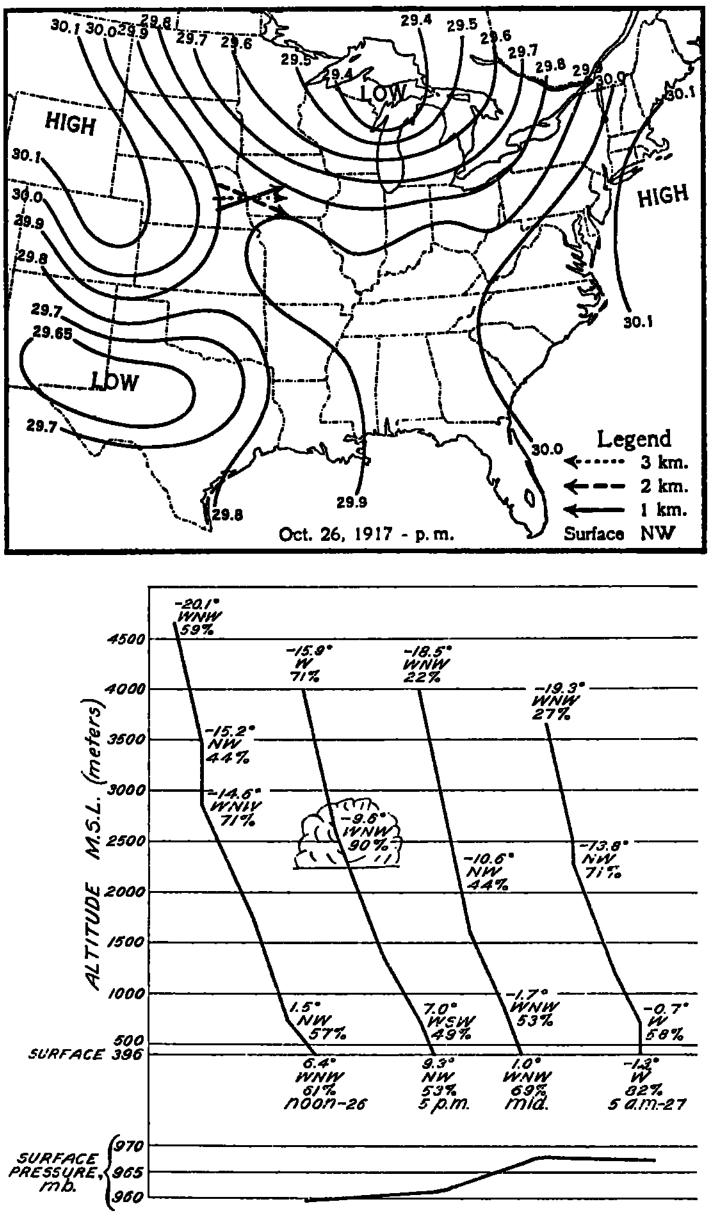

FIG. 5.—Sequence of free-air conditions at Drexel, October 26–27, 1917. Upper figure shows sea-level pressure at 7 p. m., ninetieth meridian time, October 26, and free-air winds over Drexel at approximately corresponding time

(2) The series of four flights of October 26, 1917 (fig. 5) shows the free-air conditions leading up to and following precipitation with northwest surface wind, 0.08 inch rain having occurred between the second and third flights. The second flight reveals an unbroken lapse rate, and, in the upper levels, generally higher humidity than in the first flight. This of course could not cause precipitation of consequence with the indicated wind directions, owing to their dry source. However, an abrupt surge of cold northwesterly wind in the lower levels with rapid rise in pressure, as shown between the second and third flights, was effective in causing precipitation by underrunning, the change to northwesterly

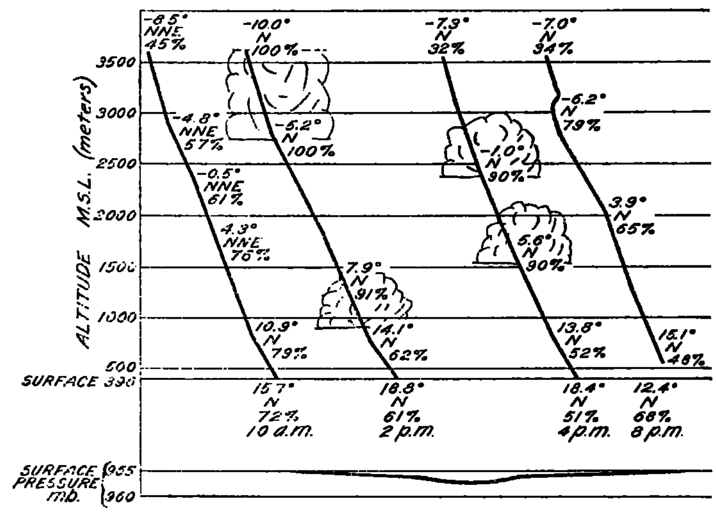

FIG. 6.—Sequence of free-air conditions at Drexel, May 19, 1919. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation

coming in the lower levels more abruptly than in the upper. It will be noted that the fall in temperature observed immediately after the rain was greatest in the low levels near the ground.

The graph of the series of four flights on May 19, 1919 (fig. 6), shows conditions immediately preceding and following a light shower (between the second and third flights) where the winds were generally north to north-northeast up to 3,600 meters altitude. As might be expected from the circumstance of deep unidirectional winds of northerly component, only a small amount of precipitation (0.01 inch) occurred, notwithstanding that it was in the form of a thundershower. The temperature-altitude curves show a diurnal rise near the ground and lower levels, and sustained low temperatures aloft. A lapse rate approaching the dry adiabatic resulted, which in connection with strata of high humidity, made the column of air unstable. The pressure was stationary except during the prevalence of the thundershower, when a slight rise occurred accompanied by a

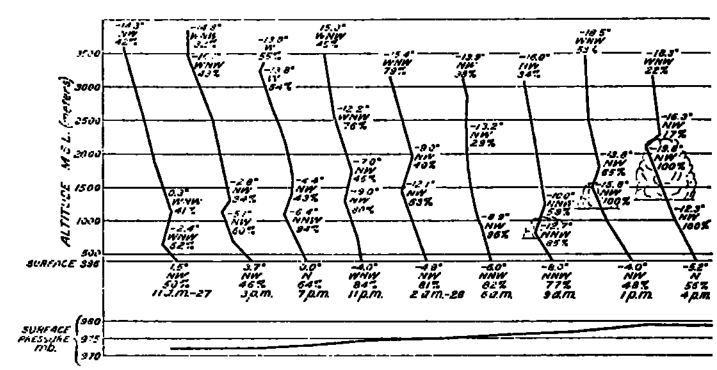

FIG. 7.—Sequence of free-air conditions at Drexel, February 27–28, 1920

decided fall in surface temperature. Evidently a slight surge in pressure was required to produce underrunning sufficient to cause precipitation. The strata of cloudiness preceding the thunderstorm were transported from regions to the east and northeast, where precipitation was already occurring north of a low pressure center a few hundred miles southeast of Drexel.

This underrunning in a northerly wind is well illustrated for a winter condition in the graph of the series of flights on February 27–28, 1920 (fig. 7). In this case, however, there was evidently insufficient lapse rate and moisture content in the northwesterly winds of upper levels to cause precipitation, so that the trace of snow that did occur formed at the top of the underrunning stratum of cold air, a process which, owing to the gradual extension of the rapid fall in temperature into higher altitudes, formed a high lapse rate, resulting in turbulence and light precipitation.

While the preceding examples of the conditions in a northerly to northwesterly wind associated with precipitation cover only three cases, they strongly suggest that when deep unidirectional winds occur from directions ranging from north-northeast to about west, but little precipitation can be expected, even in connection with thunderstorms. From the fact that considerable precipitation occurs, at least in the Middle West, with north component surface winds,[5] it is apparent that such cases of precipitation must generally be associated with other directions aloft.

(3) From the fact that most of this class of precipitation is attended by thunderstorms, free-air observations under these conditions, particularly diurnal series, are almost entirely limited to periods preceding or following occurrence of precipitation. In the series of March 30–31, 1921 (fig. 8), no strong lapse rate is apparent in the upper levels above the diurnal rise and fall in the inversion layer. Instead, there occurred a gradual veering of the upper winds from southwesterly to westerly, and, until after the 3 a. m. flight, a rise of humidity which in general occurred at progressively lower altitudes. The last curve prior to the beginning of precipitation (3 a. m.) shows that the wind veered at all altitudes, though principally near the ground, and that the fall in temperature in the lower levels (below 2,350 meters)

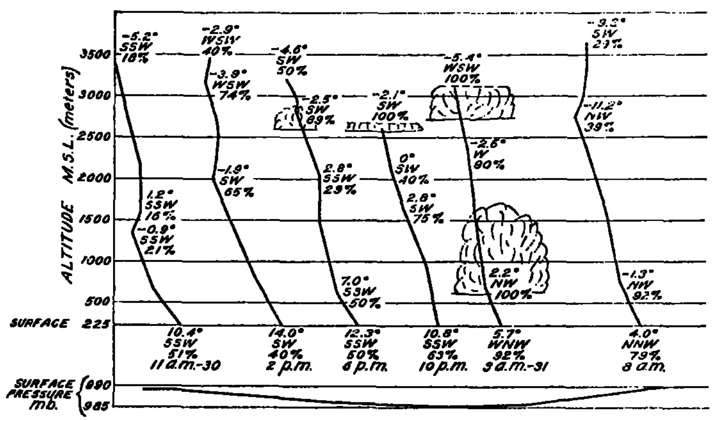

FIG. 8.—Sequence of free-air conditions at Royal Center, March 30–31, 1921. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation

incidental to the veering of wind to the northwest reduced the lapse rate to a small value. This curve shows northwest wind on the ground gradually backing to west-southwest aloft. The amount of precipitation was small (0.03 inch), emphasizing what has already been brought out, viz, that at least in the great majority of cases of northwest wind not much precipitation can occur unless there is a more or less abrupt shift above it to a southerly wind.

[5] MO. WEATHER REV., January, 1924, 52: 18–22; also Udden, Anton D., A Statistical Study of Surface and Upper Air Conditions in Cyclones and Anticyclones Passing over Davenport, Iowa, MO. WEATHER REV., February, 1923, 51: 55–68.

The graph of Figure 9 shows the records of the upper air conditions in three flights on September 5, 1923, immediately preceding a shower of the typical squall type, with abrupt change in wind direction to northerly at and near the surface. The record of humidity and temperature below about 2,000 meters is missing in the last flight, owing to the collapse of the instrument-carrying kite and consequent blurring of the record when, in the process of reeling down, the kites encountered the northerly underrunning current with its attendant strong wind and clouds. The gradual rise in humidity with

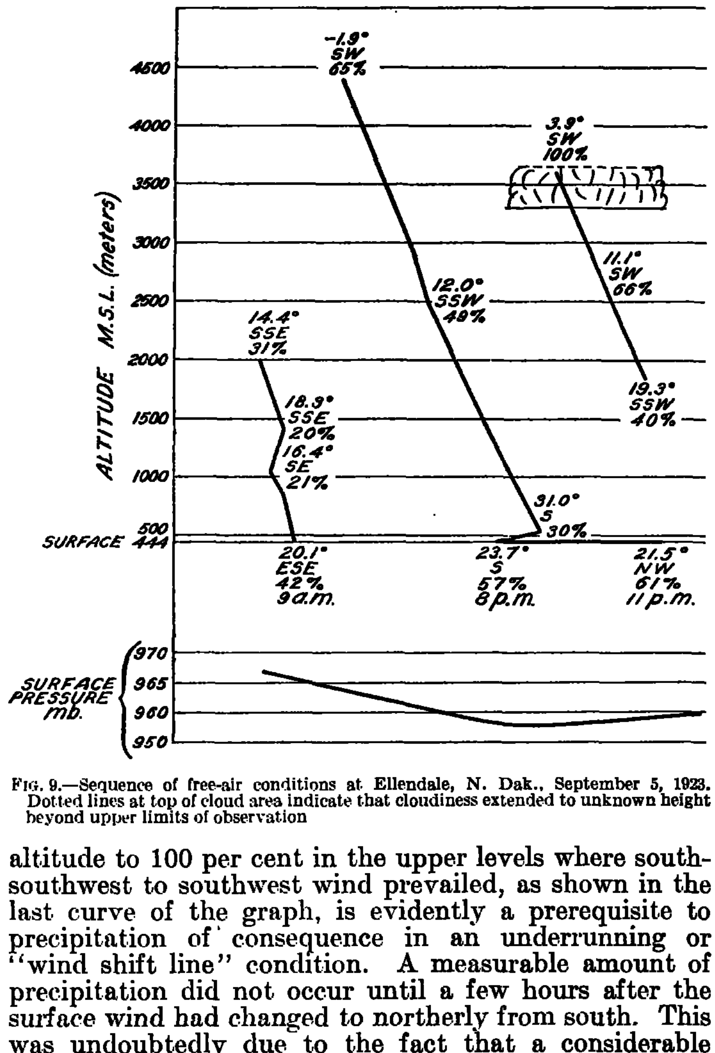

FIG. 9.—Sequence of free-air conditions at Ellendale, N. Dak., September 5, 1923. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation

altitude to 100 per cent in the upper levels where south-southwest to southwest wind prevailed, as shown in the last curve of the graph, is evidently a prerequisite to precipitation of consequence in an underrunning or "wind shift line" condition. A measurable amount of precipitation did not occur until a few hours after the surface wind had changed to northerly from south. This was undoubtedly due to the fact that a considerable depth of comparatively dry air intervened between the high strata of clouds in the south-southwest wind and the underrunning northerly current near the ground. This column had a lapse of about 0.87° per 100 meters, or close to the dry adiabatic, and exceeding the moist adiabatic for the prevailing temperature. As the column of dry air was replaced to gradually greater vertical extent by moister air and cloudiness through accumulation from southern sources, an unstable condition supervened, which needed only displacement by an underrunning colder current to cause the vertical convection necessary to precipitation.

(4) Considering those cases where precipitation occurred in winds of general southerly component in the front of a LOW, the first graph reproduced will be that of the series of flights made at Drexel on November 8–9, 1917 (fig. 10). In this series a thunderstorm developed during the last flight before the kites could be reeled in,

resulting in lightning striking and destroying the steel kite line. The outstanding feature of the series is the gradual uninterrupted rise in the height of the convection column, in which a dry adiabatic lapse rate with cloudi-

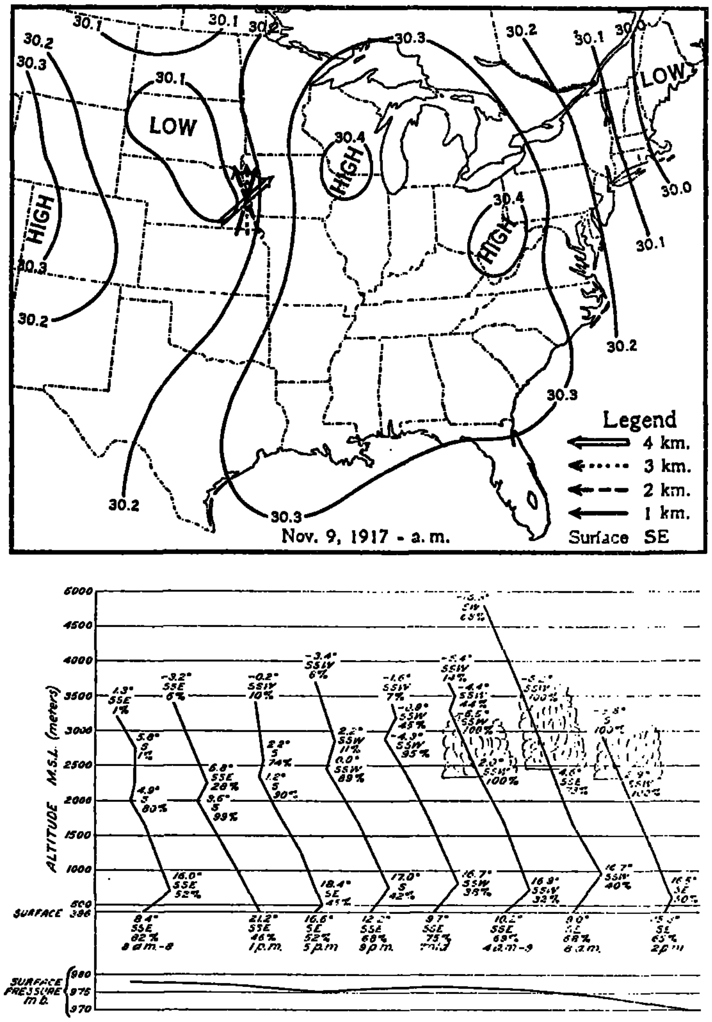

FIG. 10.—Sequence of free-air conditions at Drexel, November 8–9, 1917. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation. Upper figure shows sea-level pressure at 7 a. m., ninetieth meridian time, November 9, and free-air winds over Drexel at approximately corresponding time

ness at the top, prevailed. From the fact that this occurred throughout the night it is obvious that the maintenance of this lapse rate must be attributed to reasons other than effects of insolation at the surface. The record of wind direction shows that the top of the convection column rose because air from the HIGH to the east became replaced at successively higher altitudes by air which had recurved from the rear of the LOW. A rapid fall in pressure brought about precipitation with a thunderstorm, probably by convergence, as the rain occurred with a southeast surface wind.

The series of four flights on October 21, 1918, shown in Figure 11, was made in connection with the advance eastward of a trough of low pressure that overlay the Rocky Mountain and Plains States on the morning of that day. High humidity and cloudiness prevailed in the upper levels from the early morning, and no appreciable change in temperature occurred throughout the vertical column of air during the course of the observations. It is therefore apparent that conditions of humidity and cloudiness favorable for precipitation were transported from regions to the south where precipitation was already occurring, but that the actual occurrence of precipitation over Drexel was delayed until the position of the advancing trough of low pressure caused convergence and underrunning. This is shown by the record of surface wind direction during the 27-hour intermittent rainfall, the surface wind varying during that time from southeast, through south to southwest, and finally northeast.

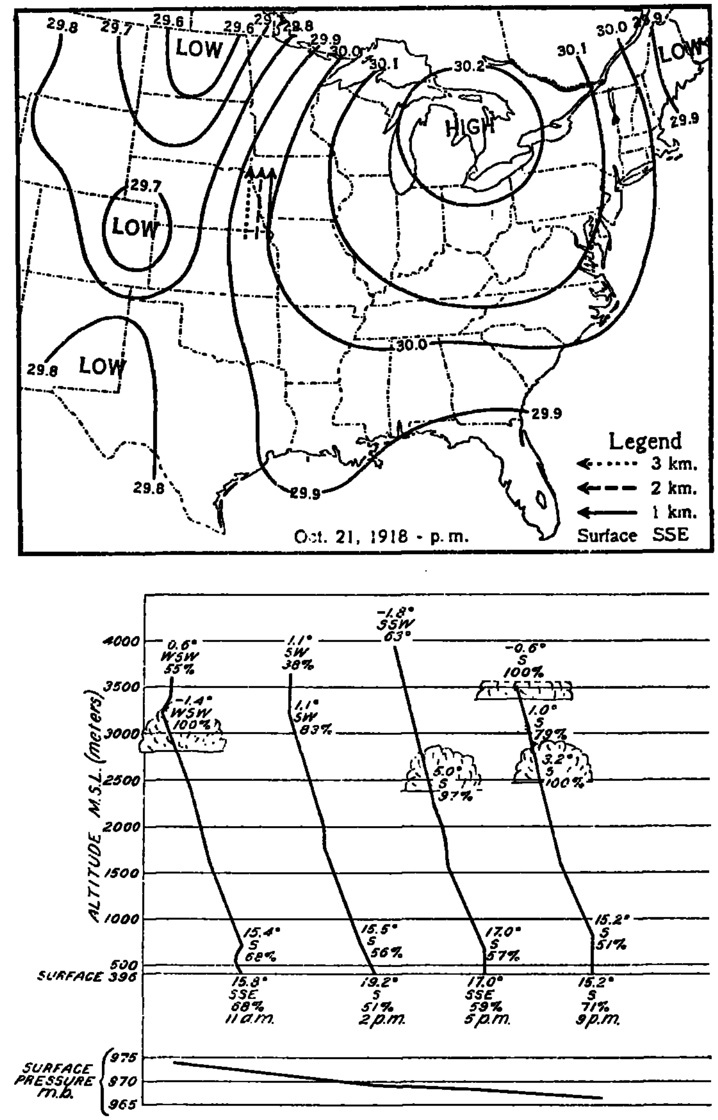

FIG. 11.—Sequence of free-air conditions at Drexel, October 21, 1918. Dotted lines at top of cloud area indicate that cloudiness extended to unknown height beyond upper limits of observation. Upper figure shows sea-level pressure at 7 p. m., ninetieth meridian time, October 21, and free-air winds over Drexel, at approximately corresponding time

The graph representing the series of November 16–17, 1922 (fig. 12) shows for the first 12 hours a dry state of the atmosphere extending to a considerable depth, and thereafter a rapid change to high humidity and cloudiness. It will be noted that the cloudiness began in the upper levels and spread to lower levels. Correlating these changes in humidity with the accompanying changes in temperature, we find a condition somewhat the reverse of that shown on November 8–9, 1917, i. e., lowering of temperature at progressively lower altitudes attending a backing of the wind from west-southwest to south-southwest. This change to colder accompanying a change from westerly to southerly is contrary to what might be expected. However, the explanation is to be found in the fact that precipitation occurred first to the south, and as the gradient changed to cause south-southwest wind, cloudiness and lower temperature were

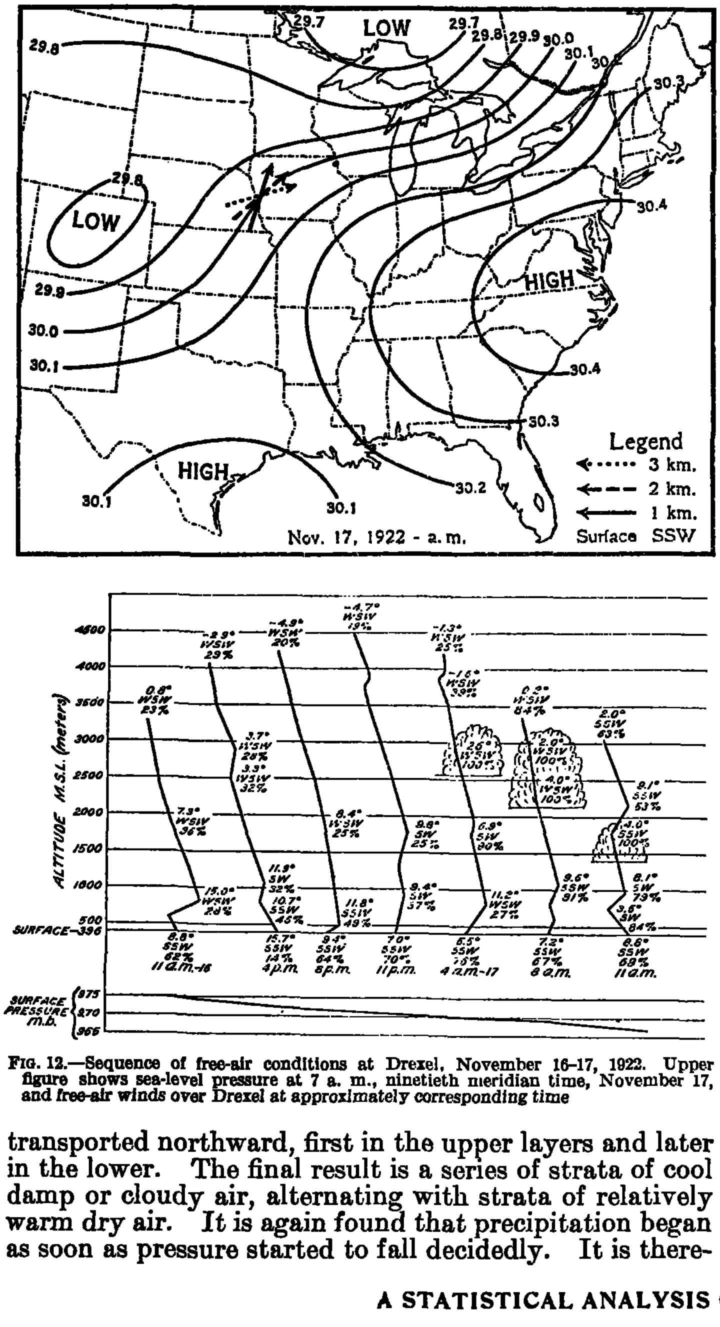

FIG. 12.—Sequence of free-air conditions at Drexel, November 16–17, 1922. Upper figure shows sea-level pressure at 7 a. m., ninetieth meridian time, November 17, and free-air winds over Drexel at approximately corresponding time

transported northward, first in the upper layers and later in the lower. The final result is a series of strata of cool damp or cloudy air, alternating with strata of relatively warm dry air. It is again found that precipitation began as soon as pressure started to fall decidedly. It is therefore probable that the mere transport of air from regions where precipitation is occurring can not of itself cause other than very light precipitation over the region affected. Whether such accumulation of clouded air is brought about in a deep layer having an unbroken lapse rate, or in a series of relatively shallow strata consisting of alternate lapses and inversions in temperature, it is apparent that in neither case is precipitation of consequence possible until there occurs the pressure change necessary to bring about forced ascent of air. The case of this series compels the opinion that rain was caused neither by instability, inasmuch as there was no deep layer having strong lapse rate in temperature, nor by ascending a slope of discontinuity, since the wind directions were very nearly uniform with altitude.

CONCLUSIONS

A feature of these graphs is the fact that but few of them show any prominent differences distinguishing them from the rest. This apparent lack of individuality is conspicuous even in cases where pronounced differences in the temperature-altitude curves and other data attached thereto would naturally be inferred. For example, while the graph of November 8–9, 1917, is one of the most striking of the collection, it is by no means typical of the general pressure situation in which it is classified; in fact it is quite closely imitated by the graph of June 12, 1917, which portrays free-air conditions under a decidedly different situation of surface pressure.

It is obvious that the most important group differences shown by the graphs pertain to seasons rather than to any other divisions, arbitrary or otherwise. The reason for this seasonal influence is easily understood by referring to tables of average free-air data, in which, particularly for continental sections, seasonal peculiarities in the vertical temperature gradients are readily identified. While the division into types is nevertheless justified, the testimony of the graphs seems to be that by whatever processes precipitation develops in a given season, the vertical structure of temperature and humidity shows substantial similarity when the precipitation stage begins.

The conclusion seems well founded that the various processes of precipitation formation ultimately resolve themselves into a free-air structure comprising strata of greater or less depth having lapse rates equal to or greater than the moist adiabatic rates for the prevailing temperatures. Notwithstanding this, consideration of precipitation types in connection with surface and free-air conditions should lead to a better understanding of the subject, to the end that these types and their development may be recognized on the weather maps.

A STATISTICAL ANALYSIS OF SOLAR RADIATION DATA

By H. W. Clough

[Weather Bureau, Washington, D. C., September, 1925]

(Read at the Washington meeting of the American Meteorological Society, May 2, 1925. Abstracted in Bull. Am. Met'l. Soc., July, 1925)

SYNOPSIS

An attempt is made to determine by statistical analysis the degree of validity of the values of solar intensity derived from pyrheliometric or bolometric observations. Both correlation coefficients and the mean dispersion of the data are employed. Certain physical relations are assumed to exist between errorless elements of data and constitute criteria for determining the validity of derived values.

Numerous correlation coefficients between both the daily values and the monthly means of solar radiation elements at Mount Wilson are presented. A high negative correlation, averaging -0.55 to -0.60, between the apparent atmospheric transmission coefficient, a and the apparent solar constant, A_0, is a feature of all daily pyrheliometric data. This is known to be due to changing transparency between low and high sun observations. A similar high negative correlation both for daily values and monthly means exists between the solar constant, E'_0, and the transmission coefficient. Since zero correlation should exist between these elements, it is inferred that the derived values, E'_0, are a function of atmospheric transparency.

A high negative correlation, -0.60, between the mean monthly values of E'_0 and A_2, is regarded as strong evidence of the unreality of the variations of the monthly values of E'_0.